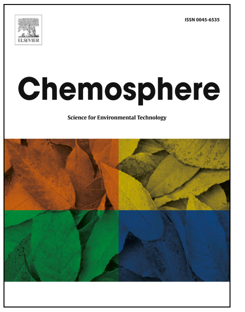

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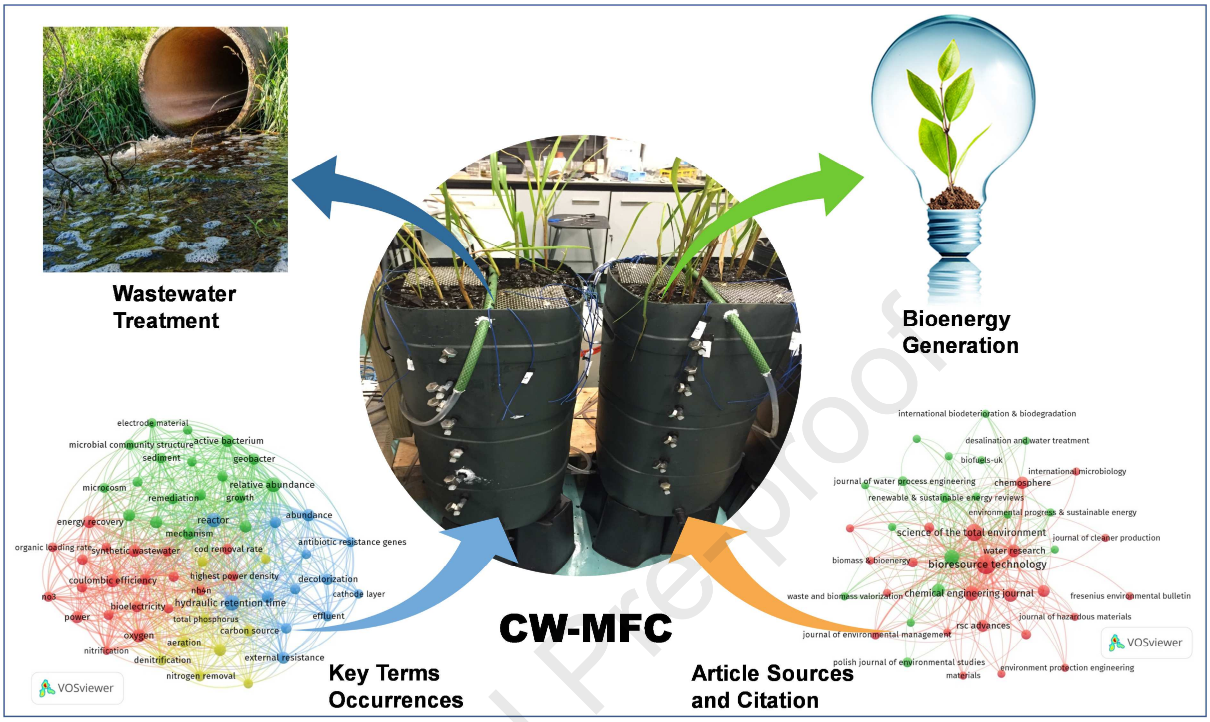
Graphical abstract



Mapping the field of constructed wetland-microbial fuel cell: A review and bibliometric analysis

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Abstract:

The embedding microbial fuel cell (MFC) into constructed wetlands (CW) to form CW-MFC bears the potential to obtain bioelectricity and a clean environment. In this study, a bibliometric analysis using VOSviewer based on *Web of Science* data was conducted to provide an overview by tracing the development footprint of this technology. The countries, institutions, authors, key terms, and keywords were tracked and corresponding mapping was generated. From 2012 to September 2020, 442 authors from 129 organizations in 26 countries published 135 publications in 42 journals with total citation of 3,139 times were found. The key terms analysis showed four clusters: bioelectricity generation performance, mechanism study, refractory pollutants removal, and enhanced conventional contaminants removal. Further research themes include exploring the biochemical properties of electrochemically active bacteria; emerging contaminants removal; effective bioelectricity harvest and the use; and biosensor development as well as scaling-up for real field application. The bibliometric results provide valuable references and information on potential research directions for future studies.

Keywords: bibliometric analysis; bioelectricity generation; constructed wetland-microbial fuel cell; VOSviewer; wastewater treatment

1. Introduction

Energy shortage and environment pollution are the two pressing issues in the modern society. Conventional environmental pollution control technologies often require high energy consuming and generate large carbon footprint. Recycling resources and energy from wastewater has become a new trend and initiative in wastewater treatment (Lam et al., 2020).

Microbial Fuel Cell (MFC) is a bioelectrochemical wastewater treatment system that uses electrochemically active microorganisms to convert the organic matters into electrical energy. In the past a few decades, MFC has been explored in various wastewater treatment for simultaneous wastewater purification and electricity production (Slate et al., 2019). The efficiency of MFC mostly depends on electrode biological reaction, however, there are still great limitations in its expanded applications (Li et al., 2018b). It is believed that the bioelectrochemical approach combined with traditional wastewater treatment technology can treat actual wastewater more effectively.

Constructed wetlands (CWs) through mimic the natural wetland environment as a green wastewater treatment technology have been developed for decades and applied for various wastewater treatments worldwide (Zhuang et al., 2019). Wastewater purification is achieved including biological, chemical, and physical processes by macrophyte plants, substrates, and mixed complex microorganisms in CWs. However, CWs also have certain drawbacks, such as large land requirement and substrate clogging etc. Therefore, it is imperative to upgrade CWs with other technique for achieving a better integrated technology (Wu et al., 2018). It seems a nature that CWs could provide suitable condition for MFC since CW has different aerobic (upper section) and anaerobic zones (lower section) (Yadav et al., 2012), which meet the requirement from principle of the MFC that a typical MFC should consist of a cathode and an anode compartments allocated in different redox conditions. Therefore, embedding MFC into CW to form CW-MFC has been developed (Yadav, 2010; Yadav et al., 2012; Zhao et al., 2013). Yadav (2010) first time reported the infant CW-MFC for treating synthetic dye wastewater under batch conditions in an international conference. Subsequently, various studies have been carried out involving the system configurations (Villasenor et al., 2013; Doherty and Zhao, 2015; Xu et al., 2016; Xu et al., 2018c); wastewater treatment (Doherty et al., 2015b; Xie et al., 2018; Kumar and Singh, 2020; Oon et al., 2020); enhancement of nutrients removal (Pous et al., 2015; Yu et al., 2015; Molognoni et al., 2017; Corbella and Puigagut, 2018; Srivastava et al., 2018; Corbella et al., 2019; Lust et al., 2020); bioenergy production (Camacho et al., 2014; Xu et al., 2018c; Tang et al., 2019; Ge et al., 2020); the operation parameters and environmental factors (Corbella et al., 2015; Xu et al., 2017a; Yakar et al., 2018; Tang et al., 2019; Yang et al., 2019; Wang et al., 2020c); electrodes materials (Wang et al., 2016; Corbella and Puigagut, 2018); enhanced biodegradation and emerged pollutant removal (Song et al., 2018; Xie et al., 2018; Li et al., 2019b; Oon et al., 2020); biosensor development (Corbella et al., 2016a; Xu et al., 2017b; Corbella et al., 2019) and energy application and recovery (Oon et al., 2018a; Oon et al., 2020); as well as greenhouse gas (GHG) control (Liu et al., 2017; Wang et al., 2019b; Zhang et al., 2020). These reflect that the CW-MFC is booming in recent years after its initial development. In recent review papers of CW-MFC, Srivastava et al. (2020a) focused on the electron transfer mechanism in electroactive wetlands, and further summarized the factors to affect the efficiency of electron movement and pollution removal. Meanwhile, Wang et al. (2020b) discussed the mechanisms of the key roles within CW-MFC for energy generation and pollutant removal. Similarly, Guadarrama-Perez et al. (2019) and Saba et al. (2019) also discussed the factors affecting the bioelectricity production and wastewater treatment, such as materials (electrode material, separators), configuration design (type of substrate and plant, microorganisms), and operation conditions (aeration, flow direction, electrode distance), as well as rhizosphere microcosmos. Ramirez-Vargas et al. (2018) reviewed the principles and the set-up methodology of microbial electrochemical technologies (MET)-based CW applied in wastewater treatment. Wang et al. (2017c) reviewed the pollutants removal enhancement and research directions of higher energy output of the CW-MFC. These review papers comprehensively summarized the latest progress in various research aspects within CW-MFC. However, the overall research trends by bibliometric analysis have not been reported.

The review based on the published literature about CW-MFC in the past 8 years (from 2012 to September 2020) using bibliometric analysis was conducted. Compared with other reviews in CW-MFC, this review provides an overview of the development footprint of this technology. It follows several aspects of: research direction which is based on key terms analysis; author's network which is according to authors/co-authorship and institutions analysis; and the source of article and high cited article analysis. The specific objectives of the review are to address three questions: (1) What is the current scenario regarding CW-MFC publication? (2) What are the key themes of CW-MFC research? (3) Which are the possible future directions of CW-MFC study based on bibliometric analysis?

2. Methodology

2.1 Data collection and preparation

Literature data collection of CW-MFC was conducted from the *Web of Science* database. The search process was divided into three steps. In the first step, the non-standard terms of “Constructed wetland”, “Artificial wetland”, “Man-made wetland”, “Treatment wetland”, “Engineered wetland” and “Reed bed” are used to refer to CW. Similarly, the term of MFC was used as relation term, such as “Microbial fuel cell”, “Electricity production”, and “Microbial electrochemical technology”, to search. In the ensuing step, terms, Boolean operators, and parentheses were used to create “TS= ("Constructed wetland" OR "Artificial wetland" OR "Man-made wetland" OR "Treatment wetland" OR "Engineered wetland" OR "Reed bed")” and “TS= ("Microbial fuel cell" OR "Electricity production" OR "Microbial electrochemical technology")” and then a search was conducted in *Web of Science Core Collection Database* with defined time period from 2012 to September 2020. The year of 2012 was selected because the first journal paper of CW-MFC was published (Yadav et al., 2012). The resultant original data were then limited by “document types = research articles or reviews” and “Languages = English”. By combining CW with MFC search results, the total of 166 documents records was obtained. Then in the final step, intensive reading was done while the redundant or irrelevant information of each document (title and abstract and main body) was filtered and removed. The screening of documents was based on the principles of: 1) The experimental device meets the CW-MFC configuration requirements, specifically with the characteristics of the CWs of substrate, plant and other elements; 2) The anode and cathode of the MFC must be embedded in the CWs system. Therefore, 135 screened journal publications were found to be sufficiently relevant. Finally, search results were exported in Tab-delimited (windows) format, which includes bibliographical information (author, title, source, abstract) and cited references to further interpreted and visualized by the bibliometric analysis software.

2.2 Data Analysis

Simple statistical analysis data, such as the number of publications per year, document types of the publications, and research category of publication, were performed through *Web of Science* platform. The download data bibliometric analysis was performed on VOSviewer software (version 1.6.15, Leiden University, Netherlands). Eck and Waltman (2010) developed this software tool for constructing and visualizing bibliometric networks of scientific publications. VOSviewer mainly generated co-occurrence networks maps which include key terms and keyword co-occurrence, and sources and citation network etc. The items are presented as a label and a circle or frame in visualization, while their sizes are depending on each term's importance. When performing co-occurrence analysis of the terms, the synonymic single words, and congeneric phrases should be re-labeling to achieve better bibliometric analysis. Based on the software manual, mapping was then generated after adjusting parameters in the program.

The key terms analysis processes of Colares et al. (2020) were followed with slight adaption. In brief, the bibliometric data were imported into VOSviewer and the terms would be extracted from the title and abstract to create a term co-occurrence map based on text data. The binary counting was used while the terms were set to recur at least five times. These terms were further screened based on 60% most relevant terms. The most relevant terms have been manually selected to excluding repeated and irrelevant items, for example, "work", "use", "research", "addition" and "month". In addition, the keywords terms of "CW, MFC, and CW-MFC" were also rule out to eliminate interference.

3. Results

3.1 Current scenario regarding CW-MFC publication

After the screening process, the number of CW-MFC publications per year, and research categories are illustrated in Fig. 1. The research articles categories were classified into four categories according to the main content of the research. They are: 1) contaminants removal and bioenergy generation; 2) energy application; 3) microbiology; and 4) structure optimize. From the chronological distribution of publications, it can be seen that the publication volume increased steadily by year. In the infancy stage (2012-2014), only 9 papers were published including 1 review paper. Yadav (2010) firstly proposed the CW-MFC conception, and investigated the removal of dye and COD and along with electricity generation in dye containing synthetic wastewater in vertical subsurface flow CW-MFC while the first journal paper was published in 2012 (Yadav et al., 2012). A year later, Zhao et al. (2013) realized the treatment of actual wastewater (swine wastewater) by CW-MFC, which achieved an average of 76.5 % COD removal and 9.4 mW/m^2 power density under influent average COD concentration over 1000 mg/L. The type of CW in most CW-MFC systems was vertical upflow as from theory the anode of the MFC should be in anaerobic condition, which was buried near the bottom of the CW to firstly contact with the influent. Whether the horizontal subsurface flow CW (HFCW) can be applied in CW-MFC was a question at infant stage until the studies reported by Villasenor et al. (2013) and Camacho et al. (2014), respectively, who studied HFCW-MFC treating synthetic wastewater. In the meantime, CW-MFC was also applied to treat refractory contaminant wastewater (Fang et al., 2013), while some scholars investigated the impact of various structural and operating factors on the performance of the CW-MFC system, such as macrophytes (Liu et al., 2013; Corbella et al., 2014), cathode materials (Liu et al., 2014), and hydraulic regime (Corbella et al., 2014). In a review of the intensified CW, CW-MFC was firstly mentioned as an enhanced CW technique for wastewater treatment (Wu et al., 2014). Since 2015, the study on CW-MFC seemed speeding up, while 25 publications were found in 2018. Compared with the infancy stage, more in-depth investigations were found in this stage. The roles of plants, substrates, microbe, and their interactions in CW-MFC have been evaluated regarding power generation and purification efficiency (Yakar et al., 2018; Guadarrama-Perez et al., 2019; Ge et al., 2020; Wang et al., 2020a; Yang et al., 2020). In addition, from the perspective of power generation and output, the materials and conditions of the electrodes as well as the connection method of MFC were also studied (Doherty et al., 2015a; Corbella et al., 2016b; Wang et al., 2017b; Xu et al., 2018d; Tang et al., 2019; Tamta et al., 2020).

[Fig. 1]

From the analysis considering the geographic distribution of authors' institution, 23 contributing countries were identified. The top 5 most productive countries presented in Table 1 are China, Ireland, USA, India, and Spain. Each has a minimum of 10 documents published, while China has published more than half of total articles (88/135). It should be noted that within our analysis time frame (since 2012) India (Yadav et al., 2012), Ireland (Zhao et al., 2013), China (Fang et al., 2013; Liu et al., 2013), and Spain (Villasenor et al., 2013) are the leading countries to study the CW-

MFC. On the other hand, although only 4 articles were published from Denmark, their citations are as high as 290, while the average citation per article is 72.5. The reason lies in a review article (Wu et al., 2014), which contributed to 251 citations.

[Table 1]

3.2 Bibliometric visualization analysis

3.2.1 Key terms analysis

In order to better grasp the research areas and tendency of CW-MFC, the analysis of the key terms of the collected data (121 research papers excludes review articles) was carried out using VOSviewer software. The generated term co-occurrence network map is illustrated in Fig. 2.

[Fig. 2]

As seen in Fig. 2, the color of the node represents a di□erent cluster, while the size of the circle reflected frequency. The terms can be divided and classified into four clusters by software. In some cases, items are not shown with the label in order to avoid overlap in a circle. The color of clusters is shown in red, green, blue, and yellow. In general, the terms in the red cluster are mainly about the studies of bioelectricity generation performance of CW-MFC. The central term in red cluster is the coulomb efficiency. The closely related terms include "bioelectricity", "electrode spaces", "energy recovery", "graphite", "closed circuit", and "open circuit", as well as "domestic wastewater" etc. The green terms in second cluster are more related to the mechanism studies of the CW-MFC. The most frequency term in this cluster is "relative abundance", such as "electrode material", "macrophyte", "microbial community", "geobacter", and "microcosm". The blue cluster constituted to the removal of refractory pollutants which is an important application of CW-MFC. For example, some items from this group included "azo dye", "decolorization", "sulfamethoxazole", "antibiotic resistance genes" and "abundance". Lastly, the yellow cluster focuses more on removal performance of conventional contaminants, where the terms such as "nitrogen removal", "total phosphorus", "total nitrogen", and "pollutant removal", as well as "carbon source" were used. Overall, the presence of these four clusters reveals the main CW-MFC ongoing research aspects that are currently conducting in global level.

3.2.2 Analysis of authors and research collaborations

Tracking articles from leading authors and/or groups is an important way to quickly understand the frontiers in this field. Based on the bibliometric analysis, some research groups are most productive in the field (Fig. 3). The group lead by Prof. Yaqian Zhao (with team members of Dr. Liam Doherty and Dr. Lei Xu, etc.) developed an alum sludge-based CW-MFC (Zhao et al., 2013). From this system, a series of studies have been carried out on improving the contaminants purification (Doherty et al., 2015b; Xu et al., 2018d); bioenergy generation capacity (Doherty and Zhao, 2015; Xu et al., 2016; Xu et al., 2018b; Tang et al., 2019), and the application of electrical energy (Xu et al., 2017b). The group lead by Prof. Hailiang Song (Nanjing Normal University, China) and Prof. Xianning Li (Southeast University, Nanjing, China) published a large number of papers which are focused on the use of CW-MFC to remove biorefractory pollutants, such as azo dye (Fang et al., 2013, 2015), tetracycline, sulfamethoxazole and sulfadiazine (Zhang et al., 2016; Song et al., 2018), and bisphenol A and ibuprofen (Li et al., 2019b). In this research direction, the group of Soon An Ong from Malaysia also published several research articles in recent years (Oon et al., 2018b; Oon et al., 2020). A research group led by Prof.

Sinshan Song from China is also active in CW-MFC investigation with wide range of aspects in CW-MFC development (Fig. 3). In addition, the rest of the organizations of the clusters are from India, Malaysia, Spain, and Turkey (see Table 1).

[Fig. 3]

The author's collaborations analysis indicates that the groups lead by Prof. Y.Q. Zhao, Prof. H.L. Song, and also a group of the CSIR Institute, India (lead by Prof. A.K. Yadav) are the typically continuous research group. Those groups initiated earliest study on CW-MFC and continued this direction of investigation till now, while the number of publication is also considerable. Some scientists have conducted a study on CW-MFC in a certain short period, such as Lu et al. (2015), Wu et al. (2015) and Khalfbadam et al. (2016). Their research has enriched the diversity of CW-MFC, but no further studies were reported. In fact, several other emerging groups are working on this field. For instance, the research group from Shandong Normal University, China (under leadership by Prof. Q. Kong), has published several studies on the pollutant removal, microbial community structure and resistance gene shift in CW-MFC in last three years (Xu et al., 2018a; Xu et al., 2019; Wang et al., 2020a). In addition, as shown in Fig. 1, the number of articles published each year is rising rapidly, and the research direction is also more diverse. Furthermore, over the time, cross-group communication became popular. Prof. Y.Q. Zhao collaborated with a few organizations in China (such as Chang'an University and Xi'an University of Technology) (Doterty et al., 2015a; Tang et al., 2019). Recent publications show that Prof. A.K. Yadav (from India) has cooperation with Dr. R. Abbassi and Dr. P. Srivastava from different research institutions in Australia (Srivastava et al., 2019; Srivastava et al., 2020a; Srivastava et al., 2020b). Overall, the research groups working on CW-MFC study show a trend of increasing and diversification, but the cooperation of authors between different institutions and countries needs to be further improved.

3.2.3 Source and citation analysis

The 135 articles are derived from 42 journals. In VOSviewer, the article sources can be seen as an item to analyse citation and then to generate a network visualization map of article sources and citations (Fig. 4). The distance between each journal in the visualization indicates the relevance of the journal in terms of related citation links, while the thickness of the line represents the link strength. *Bioresource Technology*, a comprehensive journal for environmental science and energy, was the most productive journal with 25 records. It was followed by *Science of the Total Environment*, and *Chemical Engineering Journal* and then *Ecological Engineering* with 19, 12, and 8, respectively. Apart from these comprehensive journals, some journals focusing on electrochemistry and applied microbiology are also favored by authors. For example, *Bioelectrochemistry*, *Biomass & Bioenergy*, *Biosensors & Bioelectronics*, and *International Microbiology*, *International Biodeterioration & Biodegradation*. The extensiveness of the source of the article shows that the study about CW-MFC involves the intersection of multiple disciplines. This complex system is worthy of larger and deeper exploration.

[Fig. 4]

The 10 most cited research articles were listed in Table 2. In this study, the 135 documents create 3,139 citations that include 1,284 self-citations, and the overall average citations per item are 23.25.

As shown in the Table 2, the published time of highly cited articles concentrated on

2012 to 2015, it is indicated that these studies pioneered the diverse research directions of CW-MFC. For example, Yadav et al. (2012) firstly proposed the concept of CW-MFC, Villasenor et al. (2013) successfully constructed HFCW-MFC, and Zhao et al. (2013) developed an alum sludge-based CW-MFC, while Lu et al. (2015) discussed the effects of plants and operation strategies on electricity production from the perspective of microbial community structure. In addition to these studies, other highly cited research articles have also been based on the optimization operation strategy and improvement structural of CW-MFC to enhance the performance of wastewater treatment and electricity generation (Fang et al., 2013; Liu et al., 2013; Liu et al., 2014; Doherty et al., 2015b; Fang et al., 2015; Xu et al., 2018a).

[Table 2]

By analysing the source of the highly cited article, it was found that *Bioresource Technology* and *Chemical Engineering Journal* occupied three articles, respectively. Other journals include *Ecological Engineering*, *Water Research*, and *Biosensors & Bioelectronics* as well as *International Journal of Photoenergy*. These journals have high CiteScore and Impact Factor. It suggested that researchers seem to consider publishing articles in high-quality journals to promote this field for rapid development if their study results have groundbreaking findings.

4. Discussion

4.1 Evolution and major applications of CW-MFC

To date, the review of CW-MFC is comprised of a total of 135 publications (121 articles and 14 reviews) by 442 authors affiliated with 129 organizations in 26 countries, which were published among 42 journals and cited 3,139 times. Based on the above bibliometric analysis, the roadmap towards the evolution of CW-MFC studies has been summarized and shows in Fig. 5. The first traceable research article of CW-MFC was published in the 2010 by Yadav (2010), but this concept was not created out of thin air. The discovery of using bacteria to generate bioelectrical energy from biomass has been over 100 years (Potter and Waller, 1911). A typical MFC consists of cathode and anode compartments that need to be allocated in different redox (aerobic and anaerobic) conditions. This redox condition in natural wetlands has widely existed. For example, Strik et al. (2008) presented the principle of plant-MFC to convert solar energy into green electricity. Similarly, sediment-CW was developed for simultaneous production of renewable energy and bioremediation of contaminants (Rezaei et al., 2007). CW has different aerobic and anaerobic zones which are suitable for form CW-MFC system (Yadav, 2010). Therefore, CW-MFC systems have been developed, and then deeply studied for bioelectricity production and wastewater treatment.

[Fig. 5]

From the perspective of the CW-MFC study towards large application, purification of environmental contaminants and optimization of bioelectricity production are the two main aspects (Fig. 5). Although scholars adopted synthetic wastewater containing specific pollutions to investigate the performance of pollutants removal (Yadav et al., 2012; Fang et al., 2013; Liu et al., 2013; Wang et al., 2019c; Oon et al., 2020), some complex actual wastewater, such as domestic wastewater (Corbella et al., 2014; Oodally et al., 2019), swine wastewater (Zhao et al., 2013; Doherty et al., 2015b), saline wastewater (Xu et al., 2019) and reverse osmosis (RO) concentrate (Das et al., 2019) have also been studied. Guadarrama-Perez et al. (2019) summarized that the COD removal rate is between 80 % and 95 % in a continuous flow mode in CW-

MFC. The nitrogen and phosphorus removal efficiency of 75 % and 86 % are achieved, respectively, in multi-stage hybrid CW-MFC systems (Doherty et al., 2015b). On the other hand, CW-MFC could effectively treat wastewater containing biorefractory contaminants, such as antibiotic, sulfamethoxazole as well as pharmaceutical and personal care products (PPCPs) (Li et al., 2018a; Xie et al., 2018; Li et al., 2019b; Li et al., 2020). For instance, Li et al. (2020) investigated the PPCP metabolic process and antibiotic resistance genes (ARG) accumulation characteristic under different circuit operation conditions and hydraulic retention time in the treatment of pharmaceutical wastewater by CW-MFC. It should be noted that the driver behind it lies in the unique bioelectrochemical system to stimulate microbial metabolism and enrich electrochemically active microbial communities (Ji et al., 2020). Wang et al. (2020b) pointed out that several electrochemical mechanisms may play a decisive role for enhance wastewater treatment, for example, the electron flow and electric field present in anode and cathode. Nevertheless, it has been accepted that the integration of MFC into CW could enhance pollutants removal efficiency by 27-49 % for COD (Srivastava et al., 2015), making the CW to be a compact while an intensive wastewater treatment facility to considerably compensate its drawback of large land requirement.

The maximum power density (MPD) is an important parameter of bioelectrochemical system. However, the MPD of CW-MFC tends to below than most pure MFCs' values. Wang et al. (2017c) compared the power density between pure MFC and CW-MFC through a figure, and indicated that the latter was lower in 2–3 orders of magnitude. The main reasons for this significant difference are largely internal resistance and electrode potential loss with CW-MFC (Tang et al., 2019). In order to obtain a higher power density, some optimization strategies have been proposed. Studies on electrode materials (Wang et al., 2016; Wang et al., 2017b; Sudirjo et al., 2019), electrode spacing (Doherty et al., 2015a; Fang et al., 2017a), electrode modification (Shen et al., 2018; Wang et al., 2019a), electrode conditions and connection (Xu et al., 2017a; Xu et al., 2018d; Yan et al., 2018; Tang et al., 2019; Yang et al., 2019), and separators (Xu et al., 2018c) effect on bioelectricity production capacity have been intensively conducted in recent years. In addition, roles of plants (Oon et al., 2017; Saz et al., 2018; Oodally et al., 2019; Liu et al., 2020; Yang et al., 2020), substrates (Xu et al., 2016; Fang et al., 2017b; Yakar et al., 2018; Li et al., 2019a), and microbe communities (Treesubsuntorn et al., 2019; Treesubsuntorn and Thiravetyan, 2020) in CW-MFC were also investigated in a comparison basis. Solids conclusion cannot be reached so far, but it is likely to state that the wetland plants play an important role regarding electricity generation in CW-MFC (Yang et al., 2020). Overall, due to the fact that CW-MFC is a new and complex bioelectrochemical system, which involves the physical, chemical, biological, electrochemical and their interactions, the performance would be affected by the configurations of the system, the operation parameters, and environmental factors. To this end, more multidisciplinary studies and international collaborations to narrowing the gap of knowledge are desirable.

4.2 Prospects and further research directions

To explore the latest research interesting, an overlap visualization map to co-occurrence analysis was done according to authors' keywords using VOSviewer (Fig. 6). The different colour indicates the average publication year of the documents in which a keyword represented. The yellow, orange, and red represent the last three years situation. It can be seen that many emerging authors' keywords are scattered in graphics. Combined with the previous bibliometric visualization analysis about key terms (which were extracted from the titles and abstracts of the articles) and authors' collaborations, it is more comprehensively to understand the prospects and further research directions on CW-MFC. It should be pointed out that the analysis of key terms is to show the research area and tendency, while analysis of keywords represents the authors' research interesting.

As shown in Fig. 6, the studies on the structure and function of the microbial community to the performance of the CW-MFC system are the latest interest (Slate et al., 2019; Li et al., 2020; Treesubsuntorn and Thiravetyan, 2020; Wang et al., 2020a). In addition, from Fig. 2, the study on the mechanism of CW-MFC is most concentrated on the microbial community. The electrochemically active bacteria (EAB) on the anode converting the organic matter to generate electrons (e^-) and protons (H^+) are the key factor in bioelectrochemical reactions to make the CW-MFC work. It is undoubted that the electron transfer efficiency is the key to determining the overall performance of the system. The mechanisms of microorganisms transfer electrons to the electrode have largely relied on microbial species. The EAB could work though the direct extracellular electron transfer (DEET) or mediated extracellular electron transfer (MEET) to transfer electrons (Doyle and Marsili, 2015), while non-EAB may provide small molecular metabolites substances to EAB (Wang et al., 2020b). However, significant gaps are still existed for understanding the interactions and shifting EAB and other microbial communities, especially, the mechanism of microorganism electrode electron transfer reactions in different microbe species, and its role in pollutant removal and electricity generation (Kumar et al., 2017; Wang et al., 2017a; Xu et al., 2018a; Li et al., 2019b; Rathour et al., 2019; Srivastava et al., 2020a). With the advancement of biomolecular technology, this field will be further expanded.

Furthermore, GHG control is a controversial hotspot in conventional CW (Mander et al., 2014), the GHG emissions from integrated CW-MFC systems are also worth discussing. To date, little information about this was found (Wang et al., 2019b; Zhang et al., 2020). Wang et al. (2019b) investigated the influence of CH_4 and N_2O emissions from CW-MFC and showed that MFC obviously reduced the GHG emission from CW, but the performance was significantly related to various factors, such as external resistance, organic loading, and seasonal variations. Similarly, Zhang et al. (2020) found that MFC could control the CH_4 emissions from CWs. The distinctive microbial populations and biochemical processes are possible mechanisms of reducing GHG emissions. Considering the functional positioning of CW-MFC, if energy can be recovered while reducing GHG emissions, it is an encouraging prospect, but this requires more research to prove.

[Fig. 6]

On the other hand, as an evolving technology, CW-MFC comes from a clever combination of the CW and MFC. Therefore, when predicting further research directions, it is recommended to review its parent system. The diagram in Fig. 2 shows the study on power generation performance and advanced wastewater treatment capabilities in CW-MFC. CW has been widely applied for half a century to provide an ecological process and to purify contaminants (Wu et al., 2018). At present, numerous studies have focused on the novel design configuration, operational strategies, and contaminants removal mechanisms of CW. Similarly, the CW-MFC employed to remove pollutants should also have the same trends. This mainly include: (a) enhancing the conventional contaminants (COD, N, P) removal efficiency by optimization operational strategies (Bolton and Randall, 2019; Wang et al., 2019d; Kumar and Singh, 2020; Srivastava et al., 2020b; Tao et al., 2020); (b) targeting on the removal biorefractory and emerging pollutants. As mentioned above, H.L. Song's research group is deeply studying in this aspect; (c) integrating CW-MFC with other treatment technologies, such as anaerobic reactors, sand filtration system, and membrane bio-reactor to achieve enhanced treatment efficiency (Zhang et al., 2018; Bolton and Randall, 2019); (d) reducing the land footprint of CW-MFC by novel tiered/stacked wetland system (Xu et al., 2017c; Cabred et al., 2019).

In MFC, the electrode materials and structural configurations are two main research directions (Slate et al., 2019). Many scholars have turned their attentions to the electrode materials and the optimization structures to achieve maximizing the bioelectricity generation in CW-MFC. Detailed discussion about these studies has been presented in section 4.1. Furthermore, after gaining higher MPD, one of the major issues that should be considered is how to harvest and use generated energy. It is difficult to directly use the bioelectricity for commercial purpose at current stage, while the power densities in CW-MFC are far below pure MFC. However, this does not hinder the exploring of the use of the limited power output from CW-MFC, such as electro-coagulation. Obviously, biosensor development is a more promising research point, actually, over 150 research articles about biosensor have been published in pure MFC (Md Khudzari et al., 2018), while only three articles in CW-MFC (Corbella et al., 2016a; Xu et al., 2017b; Corbella et al., 2019).

On the other hand, as regards the practice application, it should be emphasized the issue of CW-MFC scaling-up. Unlike CW, which has been widely applied with large number of field scale applications worldwide, the current CW-MFC system is in pilot-scale and lab-scale stage (Srivastava et al., 2020b; Wen et al., 2020; Xu et al., 2020). The main challenges are how to improve power densities and generate more available electricity in real-scale CW-MFC. There are many factors to affect it, but the followings may be among the reasons. They are the huge internal resistance of a CW-MFC (Doherty et al., 2015a), the insufficient electrical contact between EAB and anode (Xu et al., 2019), competition among EAB and non-EAB for electrons or nutrients (Oon et al., 2015), and the excessive growth of heterotrophic bacteria around cathode (Xu et al., 2016; Tang et al., 2019), as well as the design of the circuits which include the inherent limitations of substrates and electrode materials, the number, shape and position of electrodes (Wang et al., 2020b). Moreover, maintaining long-term performance is also a major issue for CW-MFC scaling-up due to the deterioration in performance of electrodes, especially electrode fouling (Xu et al., 2017c). Therefore, more attention should be paid to explore the relationships between electrons travel efficiency and the design of electrodes and circuits in CW-MFC.

Overall, based on bibliometric visualization analysis, study on CW-MFC shows a diversified development trend. Due to the nature that CW-MFC combines the characteristics of CW and MFC, the most research directions should be the superposition of these two technics. Fortunately, this platform is in its infancy stage, its uniqueness will be gradually uncovered with wide and deep studies.

4.3 Contributions and limitations of the current review

Bibliometric analysis is a useful tool, which can reveal the internal links of published documents, opening a new angle for us to oversee the specific research topic. It allows us to assess the prevalence and tendency of one specific research in multiple dimension manner. According to the analysis of the key terms, four research themes in CW-MFC have been identified, while the most prolific authors and cited research articles have been analysed, which can help the peers to track the frontiers in this field. In addition, the analysis of the published articles' basic growth trends, keywords, categories, journals, the roadmap towards the evolution of CW-MFC studies have been outlined. Therefore, some research directions are proposed which might be potential hot topics for future studies.

By searching terms related to CW-MFC within documents' keywords, title, abstract, and authors to retrieve literature data in the *Web of Science* platform, the results may still miss some articles. For example, some related studies might use different terms (e.g. electro-wetland), and may not be included in this database. In addition, the collected data would be further screening and filtering to obtain more related information, however, a high degree of subjectivity exists in this process. Further studies can use multiple databases to search and compare to obtain more accurate and scientific literature data. When screening and filtering search results, independent work among multiple authors may be recommended.

5. Conclusions

This study first time used VOSviewer software to conduct a bibliometric analysis of collection literature data about CW-MFC. According to the increasing number of publications and wide range of authors' affiliations, the CW-MFC studies show a diversification trend. Studies on bioelectricity generation performance, mechanism of the system and its inherent electron-bacteria community, removal of refractory pollutants, and enhanced removal of conventional contaminants are currently the main research themes. The most productive authors and research groups include Prof. Y.Q. Zhao, Prof. H.L. Song, and Prof. A.K. Yadav, etc. *Bioresource Technology* is most favoured journal by authors. Thought this, the roadmap towards the evolution of CW-MFC studies has been outlined. The topics of the mechanisms of contaminants purification and bioelectricity production chemistry closely linked with electrochemically active bacteria, GHG emissions control, and the performance of emerging contaminants removal, as well as high-efficiency harvest and the use of generated bioelectricity would be further research directions in CW-MFC.

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Figure Captions:

Fig. 1 The number of publications per year and research categories in CW-MFC

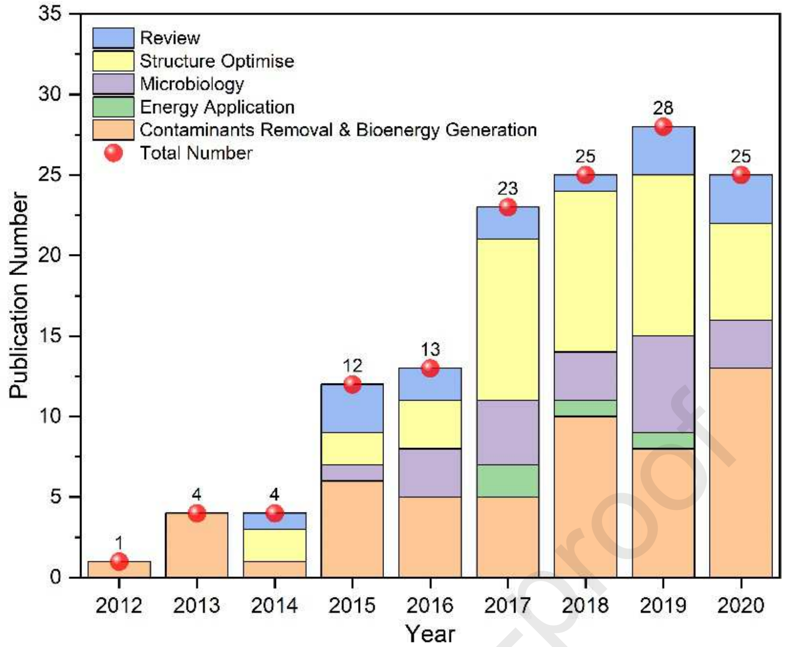
Fig. 2 Key terms occurrences network visualization map in CW-MFC. (A) Red cluster most related to bioelectricity generation performance; (B) Green cluster related to the mechanism studies; (C) Blue cluster related to the removal of refractory pollutants; (D) Yellow cluster focuses more on removal performance of conventional contaminants

Fig. 3 The map of co-authorship overlap visualization in CW-MFC studies for the period 2012-2020

Fig. 4 Article sources and citation network visualization map in CW-MFC.

Fig. 5 Roadmap for the evolution of CW-MFC studies

Fig. 6 Keywords co-occurrence overlap visualization map in CW-MFC



Review
Structure Optimise
Microbiology
Energy Application
Contaminants Removal & Bioenergy Generation
Total Number
Publication Number
Year
0
5
10
15
20
25
30
35
2012
2013
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2015
2016
2017
2018
2019
2020
1
4
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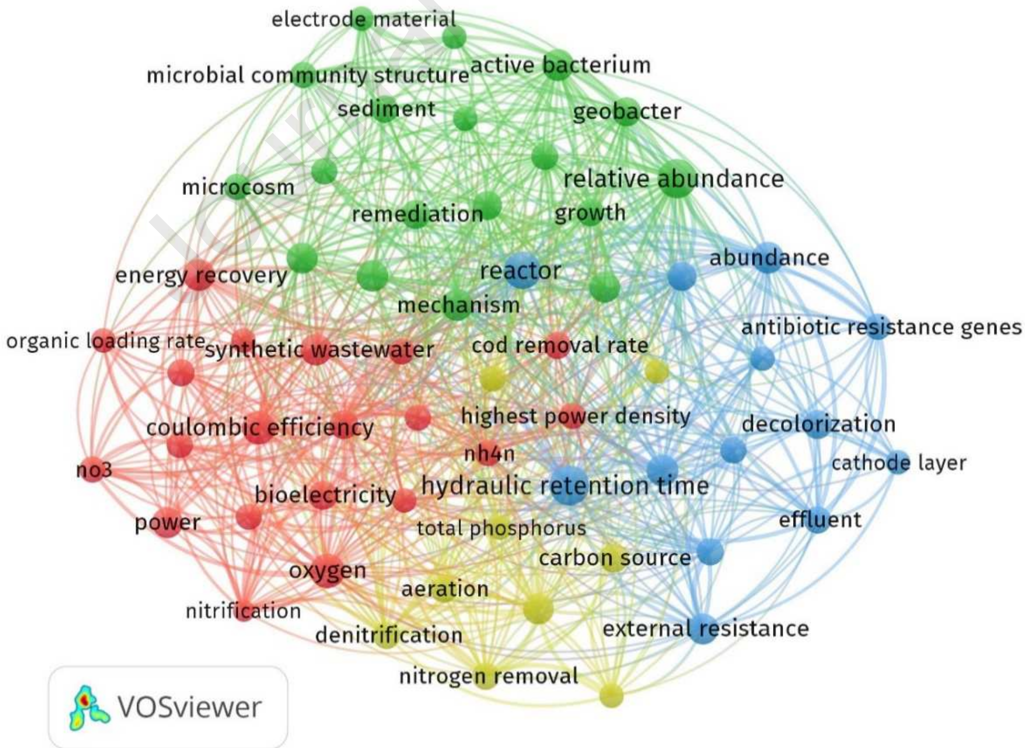
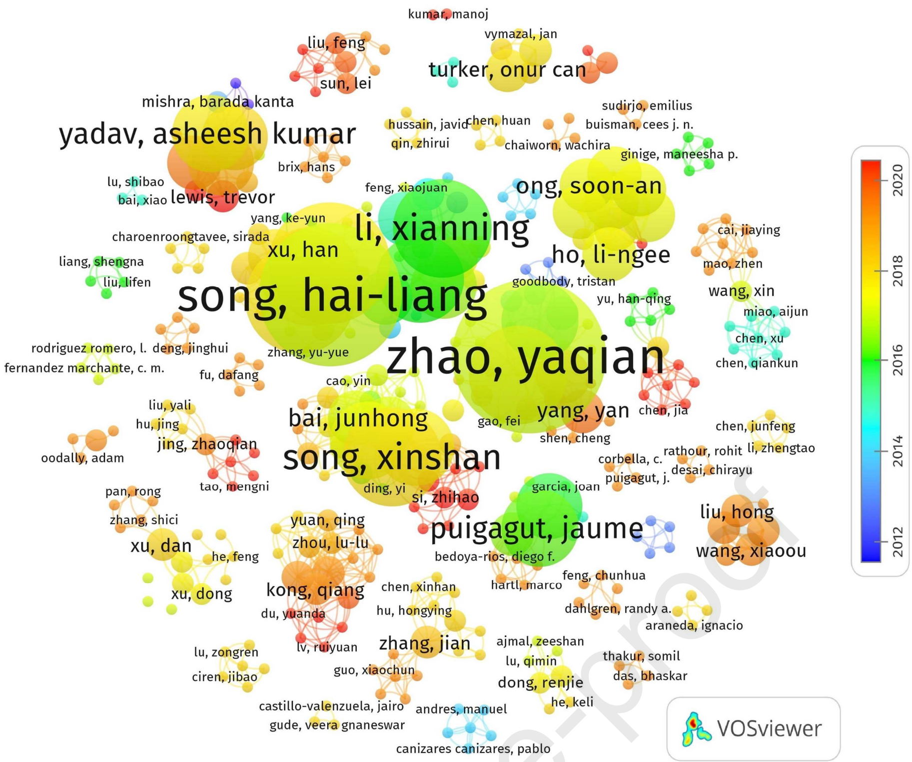
23
25
28
25

Fig. 1



electrode material
microbial community structure
active bacterium
sediment
geobacter
microcosm
relative abundance
remediation
growth
energy recovery
reactor
abundance
mechanism
organic loading rate
synthetic wastewater
cod removal rate
antibiotic resistance genes
highest power density
coulombic efficiency
decolorization
nh4n
no3
cathode layer
bioelectricity
hydraulic retention time
power
total phosphorus
effluent
carbon source
oxygen
aeration
nitrification
denitrification
external resistance
nitrogen removal
VOSviewer

Fig. 2



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vymazal, jan
liu, feng
turker, onur can
sun, lei
mishra, barada kanta
sudirjo, emilius
buisman, cees j. n.
yadav, asheesh kumar
hussain, javid
chen, huan
qin, zhirui
chaiworn, wachira
ginige, maneesha p.
brix, hans
lu, shibao
bai, xiao
lewis, trevor
feng, xiaojuan
ong, soon-an
yang, ke-yun
li, xianning
cai, jiaying
charoenroongtavee, sirada
xu, han
ho, li-ngee
liang, shengna
mao, zhen
liu, lifen
goodbody, tristan
song, hai-liang
wang, xin
yu, han-qing
miao, aijun
rodriguez romero, l.
deng, jinghui
zhang, yu-yue
chen, xu
fernandez marchante, c. m.
fu, dafang
zhao, yaqian
chen, qiankun
cao, yin
liu, yali
hu, jing
bai, junhong
gao, fei
yang, yan
chen, jia
chen, junfeng
jing, zhaoqian
shen, cheng
rathour, rohit
li, zhengtao
oodally, adam
song, xinshan
corbella, c.
desai, chirayu
puigagut, j.
tao, mengni
ding, yi
garcia, joan
pan, rong
si, zhihao
liu, hong
zhang, shici
yuan, qing
puigagut, jaume
xu, dan
zhou, lu-lu
wang, xiaoou
he, feng
bedoya-rios, diego f.
feng, chunhua
kong, qiang
chen, xinhan
hartl, marco
xu, dong
du, yuanda
hu, hongying
dahlgren, randy a.
araneda, ignacio
lv, ruiyuan
zhang, jian
ajmal, zeeshan
lu, zongren
lu, qimin
thakur, somil
guo, xiaochun
ciren, jibao
dong, renjie
das, bhaskar
castillo-valenzuela, jairo
he, keli
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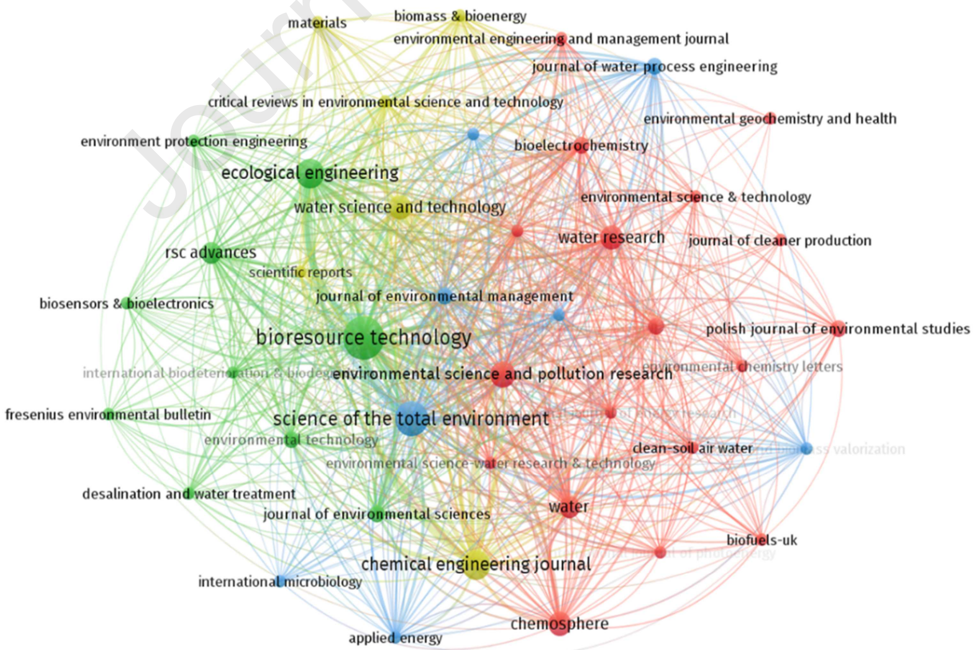
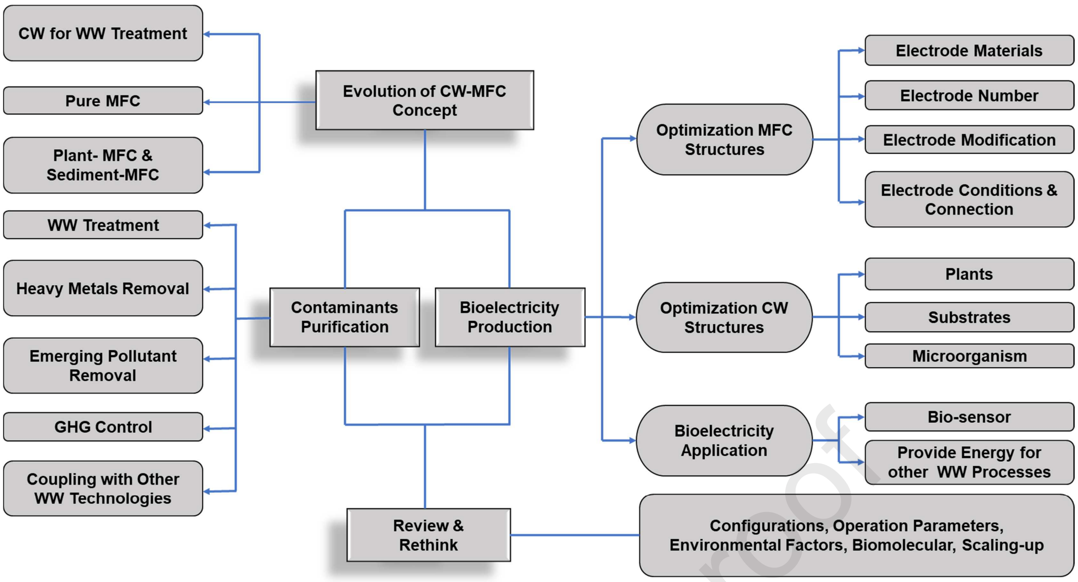
gude, veera gnaneswar
canizares canizares, pablo
VOSviewer
2012
2014
2016
2018
2020

Fig. 3



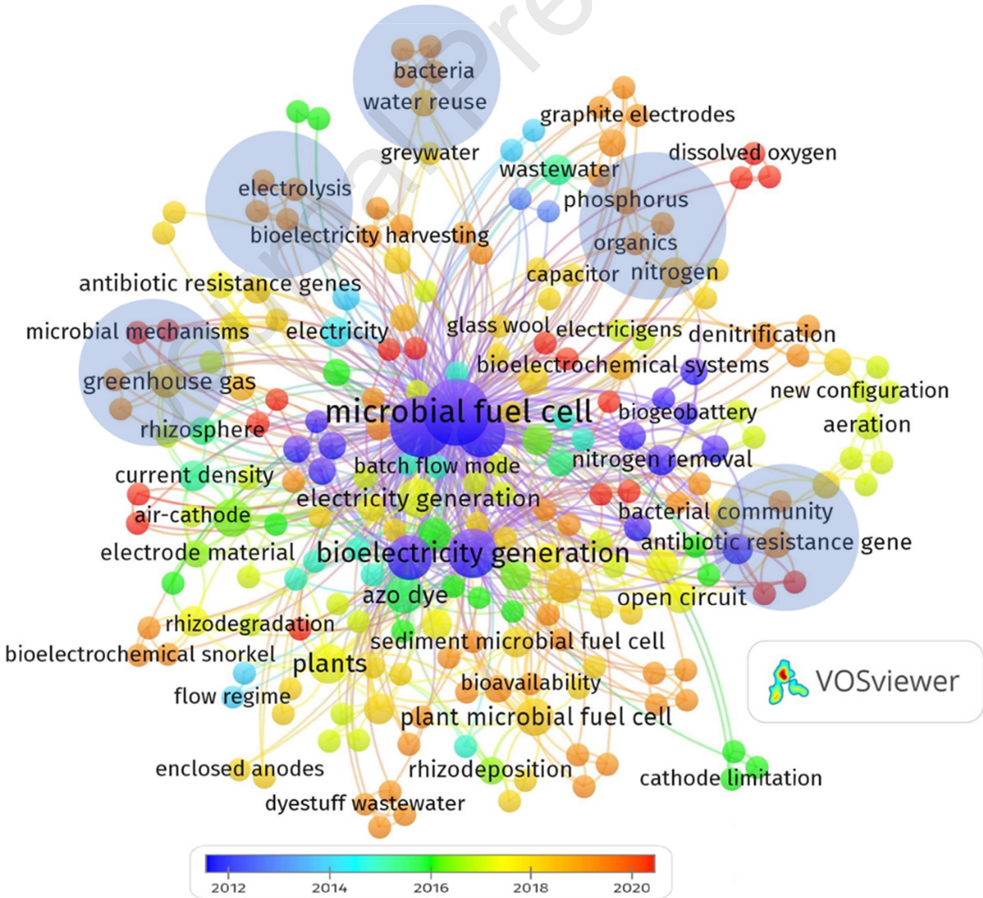
materials
biomass & bioenergy
environmental engineering and management journal
journal of water process engineering
critical reviews in environmental science and technology
environmental geochemistry and health
environment protection engineering
bioelectrochemistry
ecological engineering
environmental science & technology
water science and technology
water research
journal of cleaner production
rsc advances
scientific reports
journal of environmental management
biosensors & bioelectronics
polish journal of environmental studies
bioresource technology
international biodeterioration & biodeg
environmental science and pollution research
environmental chemistry letters
fresenius environmental bulletin
science of the total environment
environmental technology
clean-soil air water
environmental science-water research & technology
desalination and water treatment
water
journal of environmental sciences
biofuels-uk
chemical engineering journal
international microbiology
chemosphere
applied energy

Fig. 4



CW for WW Treatment
Pure MFC
Plant- MFC & Sediment-MFC
WW Treatment
Heavy Metals Removal
Emerging Pollutant Removal
GHG Control
Coupling with Other WW Technologies
Evolution of CW-MFC Concept
Contaminants Purification
Bioelectricity Production
Review & Rethink
Optimization MFC Structures
Optimization CW Structures
Bioelectricity Application
Electrode Materials
Electrode Number
Electrode Modification
Electrode Conditions & Connection
Plants
Substrates
Microorganism
Bio-sensor
Provide Energy for other WW Processes
Configurations, Operation Parameters, Environmental Factors, Biomolecular, Scaling-up

Fig. 5



bacteria
water reuse
graphite electrodes
greywater
dissolved oxygen
wastewater
electrolysis
phosphorus
bioelectricity harvesting
organics
antibiotic resistance genes
capacitor
nitrogen
microbial mechanisms
electricity
glass wool
electricigens
denitrification
bioelectrochemical systems
greenhouse gas
new configuration
microbial fuel cell
biogeobattery
aeration
rhizosphere
batch flow mode
nitrogen removal
current density
electricity generation
air-cathode
bacterial community
antibiotic resistance gene
electrode material
bioelectricity generation
azo dye
open circuit
rhizodegradation
sediment microbial fuel cell
bioelectrochemical snorkel
plants
VOSviewer
flow regime
bioavailability
plant microbial fuel cell
enclosed anodes
rhizodeposition
cathode limitation
dyestuff wastewater
2012
2014
2016
2018
2020

Fig. 6

Table 1

The top 10 most productive countries in CW-MFC study

	Country	Documents	Citations	Average Citations
1	China	88	2032	23.09
2	Ireland	18	713	39.61
3	USA	15	507	33.8
4	India	10	262	26.2
5	Spain	13	299	23
6	Malaysia	7	208	29.71
7	Australia	7	48	6.86
8	Denmark	4	290	72.5
9	Thailand	3	34	11.33
10	Turkey	3	48	16

Table 2
The top 10 cited research articles in CW-MFC study

	Title	Year	Frist Author	Corresponding author	Frist Affiliation	Country	Journal	Cited	Ref.
1	Performance assessment of innovative constructed wetland-microbial fuel cell for electricity production and dye removal	2012	Asheesh Kumar Yadav	Asheesh Kumar Yadav	CSIR-Institute of Minerals and Materials Technology	India	Ecological Engineering	137	(Yadav et al., 2012)
2	Performance of microbial fuel cell coupled constructed wetland system for decolorization of azo dye and bioelectricity generation	2013	Zhou Fang	Xianning Li	Southeast University	China	Bioresource Technology	133	(Fang et al., 2013)
3	Microbial community structure accompanied with electricity production in a constructed wetland plant microbial fuel cell	2015	Lu, Lu	Zhiyong Jason Ren	University of Colorado Boulder	USA	Bioresource Technology	106	(Lu et al., 2015)
4	Preliminary investigation of constructed wetland incorporating microbial fuel cell: Batch and continuous flow trials	2013	Yaqian Zhao	Yaqian Zhao	University College Dublin	Ireland	Chemical Engineering Journal	102	(Zhao et al., 2013)
5	Operation of a horizontal subsurface flow constructed wetland - Microbial fuel cell treating wastewater under different organic loading rates	2013	Jose. Villaseñor	Jose Villaseñor	University of Castilla-La Mancha	Spain	Water Research	101	(Villasenor et al., 2013)
6	Electricity production from Azo dye wastewater using a microbial fuel cell coupled constructed wetland operating under different operating conditions	2015	Zhou Fang	Xianning Li	Southeast University	China	Biosensors & Bioelectronics	99	(Fang et al., 2015)
7	Nutrient and organics removal from swine slurry with simultaneous electricity generation in an alum sludge-based constructed wetland Incorporating microbial fuel cell technology	2015	Liam Doherty	Yaqian Zhao	University College Dublin	Ireland	Chemical Engineering Journal	94	(Doherty et al., 2015b)
8	Power Generation Enhancement by Utilizing Plant Photosynthate in Microbial Fuel Cell Coupled Constructed Wetland System	2013	Shentan Liu	Xianning Li	Southeast University	China	International Journal of Photoenergy	92	(Liu et al., 2013)
9	Electricity production and evolution of microbial community in the constructed wetland-microbial fuel cell	2018	Xu Fei	Qiang Kong	Shandong Normal University	China	Chemical Engineering Journal	81	(Xu et al., 2018a)
10	Bio-cathode materials evaluation and configuration optimization for power output of vertical subsurface flow constructed wetland - Microbial fuel cell systems	2014	Shentan Liu	Xianning Li	Southeast University	China	Bioresource Technology	80	(Liu et al., 2014)

Highlights

- First time bibliometric analysis of CW-MFC was conducted.
- Four clusters including bacteria community and refractory pollutants removal were identified.
- Leading groups of CW-MFC study were identified.
- *Bioresource Technology* is most favoured journal by authors for publishing CW-MFC studies.
- Electrochemical-bacteria chemistry, effective electricity harvest & use are further study needs.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: